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Effect of Pulsed Blowing on Farfield Noise

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by

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Executive Summary

This portion of the report documents the results of an experimental program, which focused on pulsed blowing from the trailing edge of a CCW. The main objective of this study was to assess whether pulsed blowing resulted in more, less, or the same amount of radiated noise to the farfield. *Results show that a reduction in farfield noise of up to 5 dB is measured when pulse flow is compared to steady flow for an equivalent lift configuration.* This reduction is in the spectral region associated with the trailing edge jet noise. This result is due to the unique advantage that pulsed flow has over steady flow. For a range of frequencies, more lift is experienced with the same mass flow as the steady case. Thus, for an equivalent lift and slot height, the pulsed system can operate at lower jet velocities, and hence lower jet noise.

At low frequencies (below 1 kHz), the pulsed flow configuration generated more noise in the farfield. This is most likely due to the pulsing mechanism itself. Since the high pressure air feeding the pulsing mechanism was first passed through a high performance muffler, it is likely that this increase is not due to upstream valve noise. Most likely, the impulsive component of the air that periodically fills the plenum causes a broadband source that reaches the farfield. Although the benefit of a pulse trailing edge jet is evident from a mass flow usage and jet noise perspective, attention should be paid towards the design of a viable pulsing system. Future research program in this area should concentrate on the development of a “quiet” pulsing device.

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1.0 Introduction

The first year of this grant focused on the farfield acoustic ramifications of steady blowing from the trailing edge of a two-dimensional wing¹. By replacing a convention flap system with a rounded Coanda surface, a powerful high-lift device is produced. Studies have shown² that this type of circulation control can outperform the high lift capability of conventional flaps. The purpose of examining this type of high lift system is the expected acoustic benefit resulting from the removal of a flap system, which is believed to be a significant contributor to airframe noise on approach. Results from the first year of this grant showed that for an equivalent lift, the Circulation Control Wing (CCW) produced less noise than a wing with a conventional flap system. It was also found that proper design of the internal blowing plenum can be crucial in trying to minimize farfield noise.

The positive results of the steady blowing lead to the following question: Since compressed air for the blowing is expensive (typically, a parasitic bleed of a gas turbine), can the amount of air required be reduced by pulsing the air? Ideally, by using a square-wave pulse, half of the mass flow would be needed produce the same performance. This begs a second, more important question: Would a pulsing flow produce more, less, or about the same radiated noise to the farfield. The experimental program documented here attempts to answer this question.

Among the pertinent results presented in this report, one finding became obvious. The development of a pulsing actuation system that simultaneously provides adequate frequency response, pulse quality, and *quiet* operation is a significant challenge. Indeed, much of the work for this part of the grant was driven by this challenge. While an actuation device was ultimately used that performed adequately, a separate program to develop an actuator with the unique design requirements is needed. The challenge to produce an adequate pulse actuator was documented previously in the second year's report³. Among other issues, the frequency response (or lack thereof) of the actuator plays a crucial role. If the actuator pulse train quality deteriorates in the frequency range of interest, equivalent comparisons are difficult. Furthermore, actuator self-noise or related noise can interfere with the measurement of the jet noise from the trailing edge slot. Steps taken to address these concerns were outlined in the second year's report and included flow-straightening foam in the slot plenum and a reduction of

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the plenum volume. The latter measure was undertaken to minimize the capacitive effect (damping) of the plenum on the pulse shape.

Solenoid valves were used initially; however, they had a very small frequency range over which a reliable, quality pulse could be generated. This limit was below 20 Hz. This was primarily due



Figure 1.1. Electro-Mechanical torque-motor.

to the relatively large mass flow being used. The solenoid performance degraded with high line pressures. Moreover, the solenoids tended to overheat and fail complete after many hours of operation. Because of these drawbacks to the use of solenoids, a new type of actuator was employed for testing. A torque-motor device was used to create a pulsing flow that could be brought into the wing's blowing plenum. The torque-motor is an electro-mechanical device that takes air at high pressure as input and distributes the air alternately through two output ports. A shuttle valve is used to open and close each port. The frequency of the opening and shutting of a port is dictated by an electronic signal

input to the device. Figure 1.1 shows the torque-motor. Each output from the torque-motor is 180° out of phase with each other. It is with this device that pulsed air is ejected from the 2D airfoil used in the present program.

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2.0 Technical Approach

Farfield Acoustic Measurements and Pulse Blowing

The test article for the pulse blowing study was the same 2D airfoil used in the steady blowing

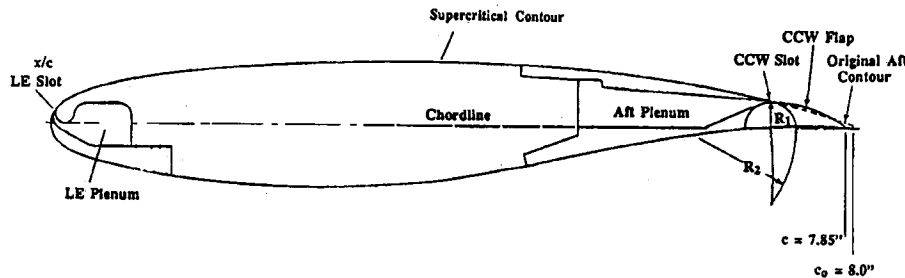


Figure 2.1. Cross section view of 2D wing used for blowing tests.

program reported earlier. Figure 2.1 shows a cross-sectional drawing of the basic airfoil. In an effort to reduce the trailing edge slot plenum

volume, the wing was modified so only the middle 12 inches of the span would be used for air flow. The reduction in plenum volume would help reduce the damping of the pulsed velocity amplitude. Figure 2.2 shows the basic airflow path of the control air. Since the plenum volume would be reduced, it is imperative that velocity be as uniform as possible through the slot exit. At the back of the plenums, a strip of aluminum foam was installed to evenly distribute the slot exit velocity. Previous work³ established this and Figure 2.3 shows the results of the addition of aluminum foam.

Since the torque-motor output is 180° out of phase, two torque-motors were used for each 6-inch

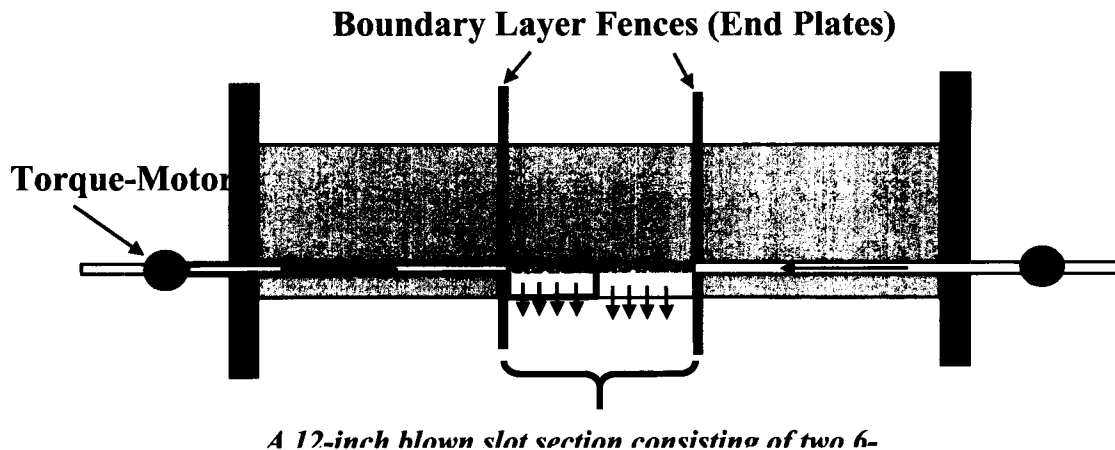


Figure 2.2. Modified internal flowpath for CC Wing for pulsed slot blowing tests.

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section of the slot plenum. This meant that one output leg of each torque-motor was “dumped overboard”. That is, the out of phase leg was allowed to exhaust into the ambient air. In order to avoid certain jet noise contamination, these outputs were run through 25 feet of copper tube coil and exhausted into a foam lined muffler.

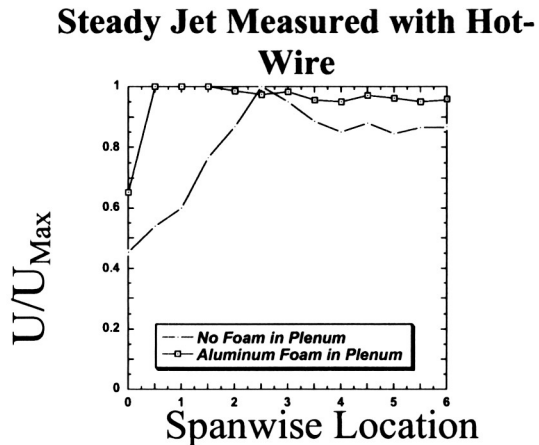


Figure 2.3. Improved flow uniformity with Aluminum foam in

The 2D wing was installed in GTRI's Anechoic Flight Simulation Facility (AFSF). The wing was exposed to freestream velocity by installing it in the exhaust region of a 28-inch diameter nozzle issuing into the anechoic room. Farfield microphones record noise levels in the farfield for several freestream velocities, slot exit velocities, and pulsing frequencies. All tests were conducted with the wing at zero angle of

attack. Figure 2.4 shows this test set-up in the AFSF.

There are essentially two ways to assess the acoustic performance of a pulsing Circulation Control wing.

- 1) Compare the farfield spectra of a steady blowing case versus a pulsed blowing case where the averaged C_μ of the pulsed case is equivalent to steady C_μ value.
- 2) Compare the farfield spectra of a steady blowing case versus a pulsed blowing case where the peak C_μ of the pulsed case is equivalent to the steady C_μ value.

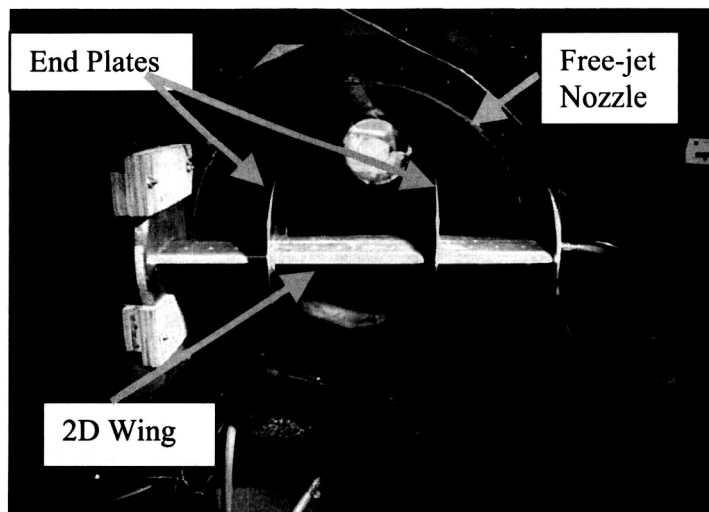


Figure 2.4 Blown 2D wing installation in Anechoic Flight Simulation Facility.

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Figure 2.5 shows schematically what ideal C_μ time histories would correspond to cases 1 and 2 above.

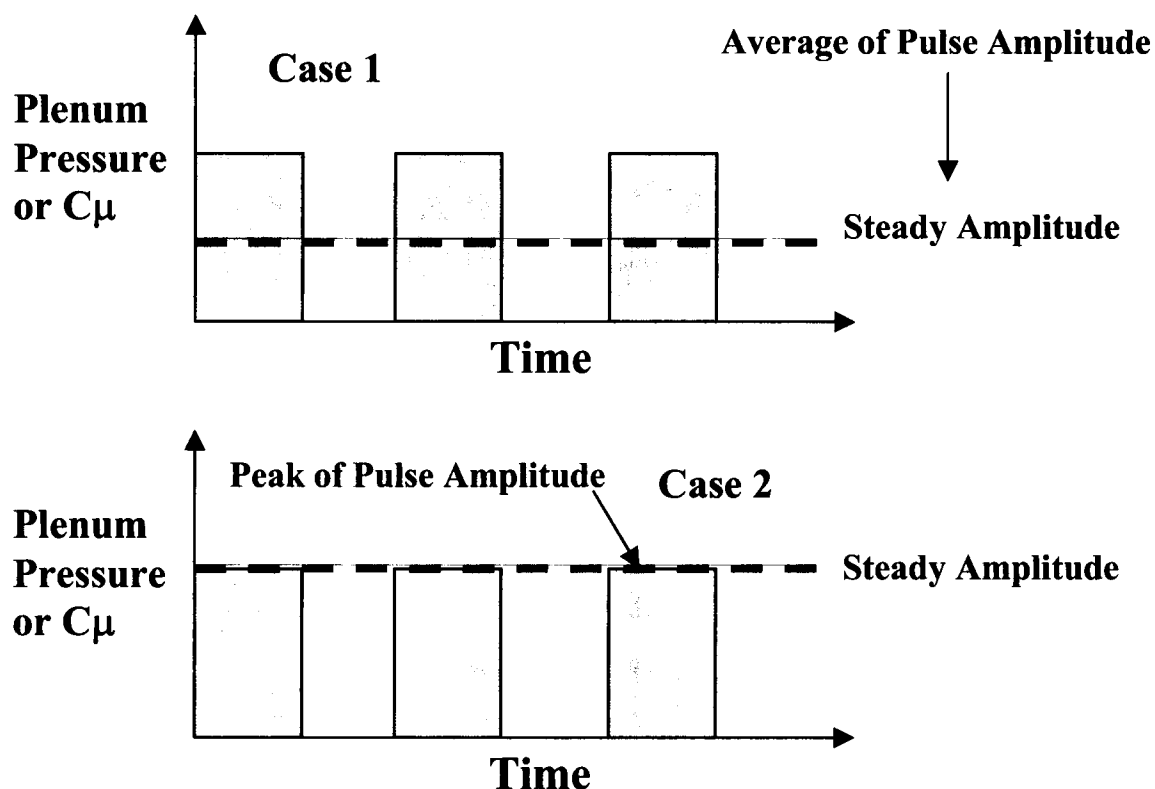


Figure 2.5. Schematic of two possible cases for comparing steady to pulsed blowing in assessing farfield acoustic performance.

It would appear that the first case above is relevant if one assumes that aerodynamically the response of the airfoil to a steady C_μ is equivalent to the response of an unsteady C_μ . Simply put, if the average C_μ (and thus C_L) the wing experiences is the same, then the lift generated should be the same.

Aerodynamic Benefits of Pulsed Trailing Edge Blowing

Work performed at GTRI under NASA LaRC Grant⁴ demonstrates that case 1 is not necessarily desirable. This grant evaluated the identical wing configuration in a wind tunnel. The wing was installed on a balance and lift was measured for a variety of pulsing and steady blowing conditions. Results confirmed earlier findings by Rockwell⁵ that over a certain range of C_μ or

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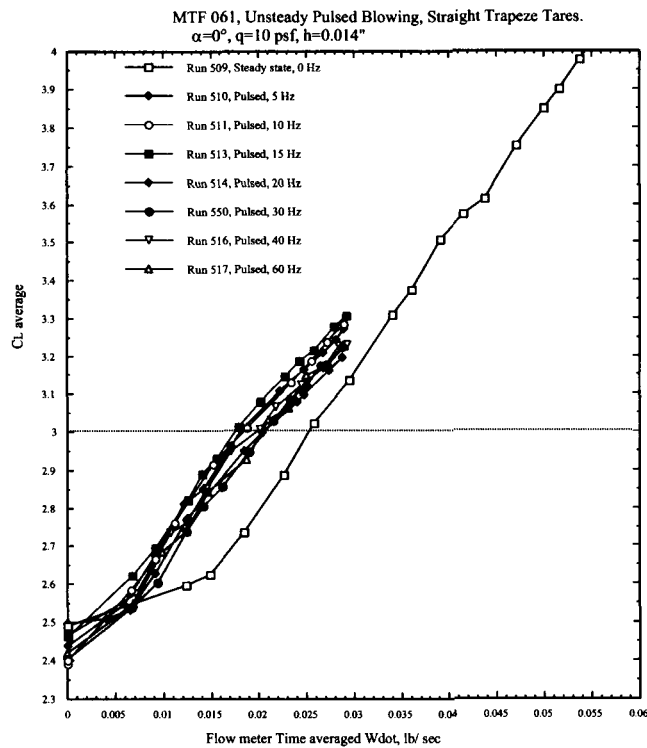


Figure 2.6. Effect of pulse blowing on lift as a function of blowing mass flow (from ref. 4).

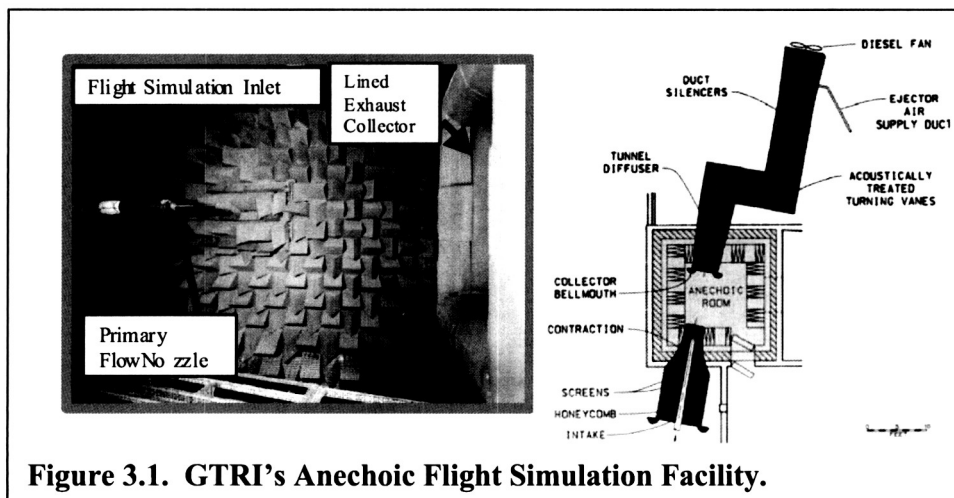
mass flows, pulse blowing produces *higher* lift than steady blowing. Figure 2.6 shows this remarkable result by showing mass flow vs. lift coefficient for a range of frequencies. There is an effect of the pulse frequency. It appears that the increase in lift seen when pulsing diminishes somewhat as the frequency increases. It is not known exactly why this is the case, but the quality (or lack thereof) of the pulse at high frequency is most likely the reason. To understand why a benefit is realized, one needs to consider the two type of pulsing comparisons outlined above in Figure 2.5. Consider the pulse train shown for case 1. The averaged

momentum ratio, C_μ , is the same in both the steady and pulsing conditions. Thus, for a constant slot height, this means that the mass flow rates are equivalent. However, for at least half of the time, the momentum ratio is roughly twice as high as the steady condition. This means that the airfoil has higher lift during this time. Averaged over some period, the pulsed blowing case experiences a higher lift as demonstrated by the results in Figure 2.6. Another way to look at it is that for equivalent lift, less momentum ratio and hence less mass flow is required for the pulsing case. The implication of this improved aerodynamic benefit is positive. For an equivalent lift system, less mass flow is needed for the pulsing case, implying therefore that (for a fixed slot height) the slot jet velocity will be lower. This should lead to a lower contribution from jet noise in the farfield relative to a steady blown case.

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3.0 Test Facilities, Instrumentation, and Data Acquisition

The farfield acoustic measurements were acquired in GTRI's Anechoic Flight Simulation Facility. This is an open jet wind tunnel housed in an anechoic chamber. The interior of this facility is shown in Figure 3.1. The flow for simulating flight is generated through the working



section in the anechoic room by the operation of a jet ejector and/or a diesel driven fan. Air is drawn into the intake at the left through the honeycomb and screens to the

contraction (see Figure 3.1), across the anechoic room to the collector, through the diffuser, the two right angle corners with acoustically treated turning vanes, the duct silencers, and the transition section to the powered exhaust section. The facility is capable of providing continuous free jet velocities up to 100 m/s with a circular test section diameter of 0.71 m. It is possible to make acoustic measurements on a circular arc of 3 m radius, centered on the model, in the range 30° to 100° with respect to the tunnel axis. The angular range may be increased by reducing the arc radius for a few measurement locations at the higher angles.

Auxilliary air used for the trailing edge blowing was supplied from a 125 psig source. The flow rate was measured with a venturi flow meter and then allowed to pass through a large muffler designed to significantly reduce any upstream valve noise. The flow was split and each leg was fed into a torque-motor. Figure 3.2 shows a schematic of this set up.

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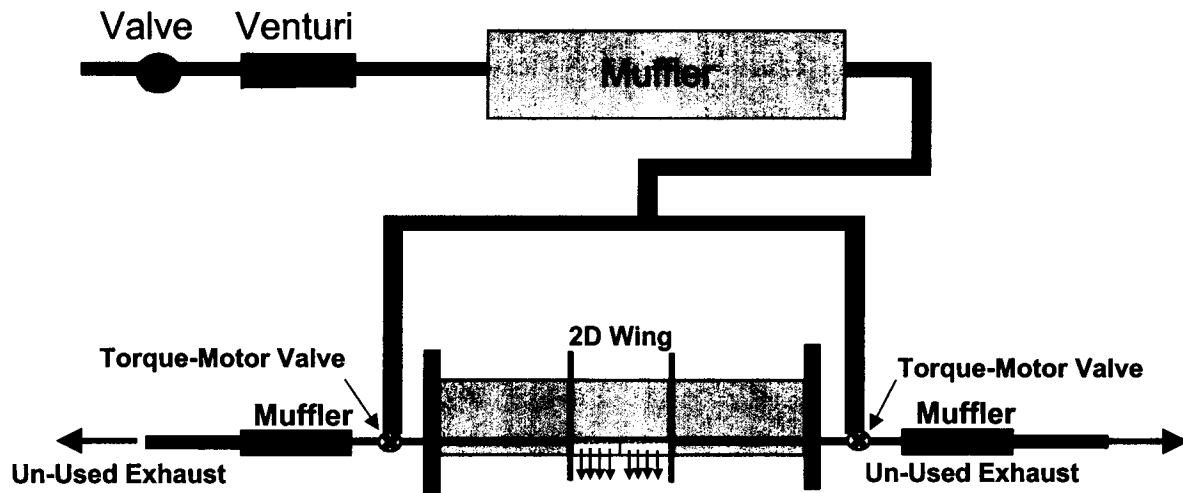


Figure 3.2. Test set up for pulsed blown wing.

Data Acquisition

Flow Data

Unsteady pressure transducers (Kulite and Endevco) were used to measure the venturi pressures as well as the plenum pressure in the trailing edge of the wing. These transducers were powered by a battery and input into a computer A/D board. Facility ambient pressure and temperature were monitored. The simulated freestream velocity was computed from static pressure measurements made around the circumference of the nozzle bringing air into the facility. A Labview data acquisition program was written on a Windows platform to collect the pressures from the venturi and the wind tunnel. Mass flow to the wing was computed via venturi flow analysis. Steady tunnel pressures were acquired with a PSI multi-channel pressure transducer. All flow data was stored in retrievable files on the computer.

Acoustic Data

Acoustic data were acquired with 1/4-inch B&K condenser microphones using B&K Nexus power supplies and amplifiers. These microphones were placed on a polar arc directly beneath the wing model. Using the facility's jet exhaust axis as the 0° polar angle, eight microphones were placed 10° apart from 100° to 30° . Figure 3.3 shows this set up. All microphones except

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the 100° and the 30° were located 10 feet. The data from the 100° and 30° microphones were corrected to a distance of 10 feet. Furthermore, all acoustic data was corrected for atmospheric absorption, free-field response, and the microphone grid effect. Pressure time histories were acquired on an HP 3667A Multi-Channel Signal Analyzer for FFT analysis running on a Pentium-based Windows computer platform.

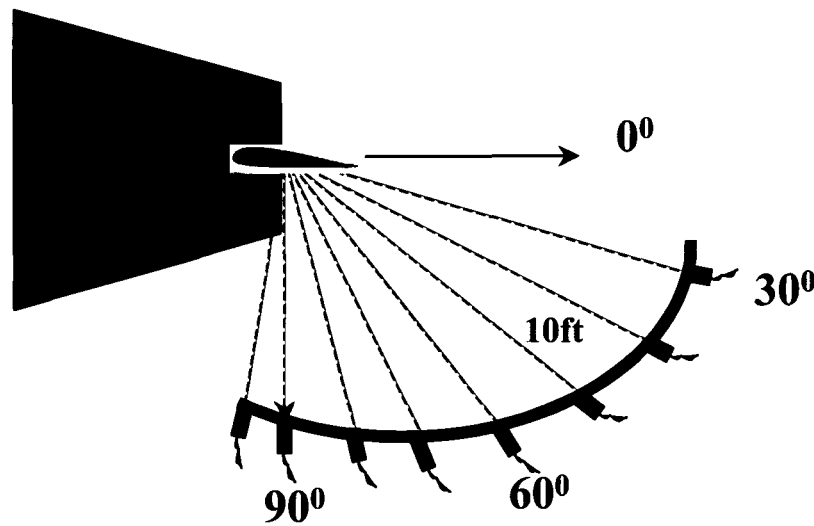


Figure 3.3. Farfield microphone set-up in Anechoic Flight Simulation Facility.

4.0 Pulse Actuator Performance

The torque-motor used in the present pulsed blowing experiments produced slot exit velocity characteristics that were, in general, more repeatable than the problematic solenoid valves. While the ideal goal of perfect square waves (as shown above in Figure 2.5) is unobtainable, reasonable pulse quality was obtained from the device. Figure 4.1 shows typical slot exit velocity time histories measured with a hot wire. A Kulite pressure transducer installed in the slot plenum was also used to gauge the pulsing velocity. Figure 4.2 shows a typical plenum pressure history.

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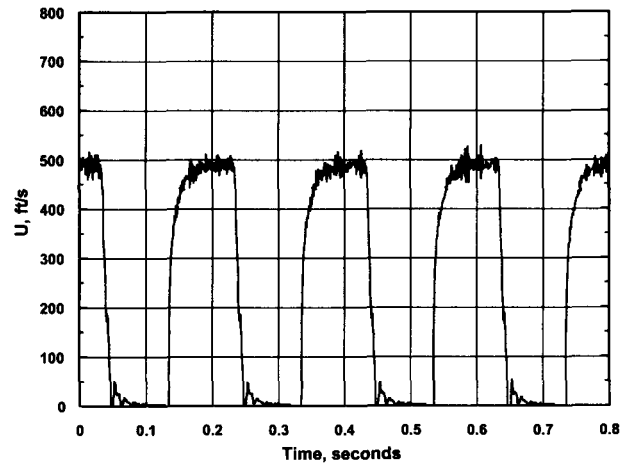


Figure 4.1. Slot exit velocity time history for 5 Hz pulse, measured with hot wire.

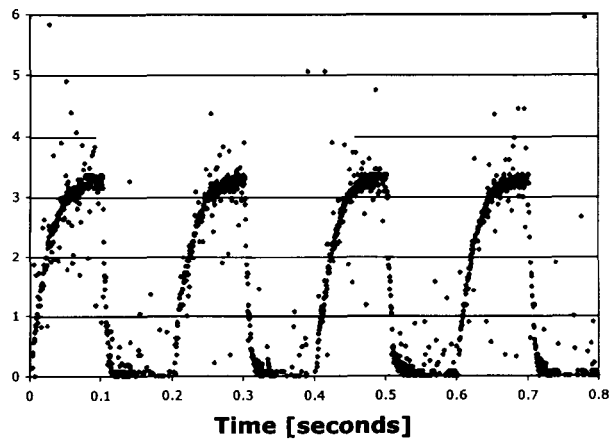


Figure 4.2. Plenum pressure time history during 5 Hz pulsing.

It is noted that there is a rounded ramp-up to the maximum pressure before a relatively sharp drop to near zero pressure. It is believed that this is due to finite time needed to fill the plenum with air. The DC offset was nearly zero for low frequencies but was on the order of 0.2 psig above 30 Hz.

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5.0 Farfield Acoustic Results

The main objective of this study was to discern the differences (if any) in the farfield acoustic spectra of a Circulation Control wing under steady trailing edge blowing from unsteady (pulsed) blowing conditions. While microphones in the farfield were stationed from 110° to 30° at 10-degree increments along the chord-line axis, data presented here will consist mostly of the 30, 60, and 90-degree locations. It is the noise from the jet issuing from the trailing edge slot, which is of interest. Most of the noise generated from a high-lift wing employing circulation control in this way will be attributed to this jet noise. Thus, it is important that the farfield acoustic measurements indicate this jet noise component. There will be contributions from the free-jet issuing into the anechoic room, the wing itself, and its mounting hardware. Due to the characteristic dimension of the high-speed jet exiting the trailing edge (approximately 0.014 inches), it is expected that the noise generated by this jet will be at frequencies exceeding 20 kHz.

Verification that the slot exit noise is discernable in the farfield spectra can be observed in Figure 5.1. This figure shows spectra for five cases: background ambient, wing mounted with NO blowing, and wing mounted with steady blowing at three separate mass flow conditions. Since slot height is constant, each mass flow case represents a different jet

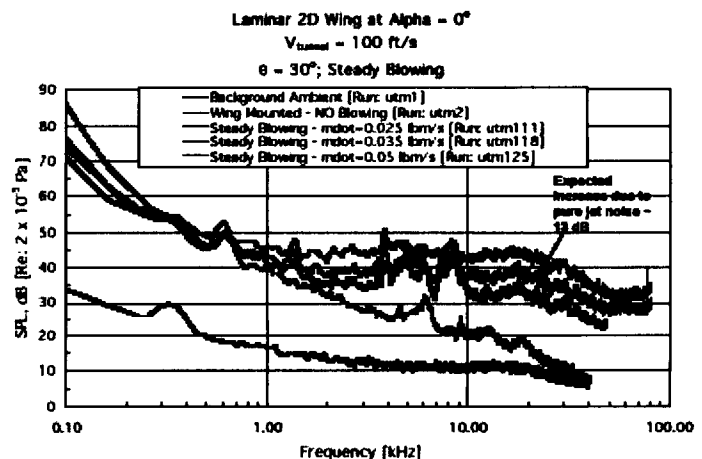


Figure 5.1 Presence of slot jet noise in measured farfield spectra.

velocity. It is clear that the noise at the lower frequencies is due to the free jet and the wing alone (any contribution of the slot jet is too low to impact spectra at these frequencies). However, it can be seen that above approximately 10 kHz, the noise from the jet operation is distinct. Furthermore, jet noise theory predicts that the amplitude should increase by $80 \log(\text{Jet Velocity})$. It is estimated that the increased mass flow case should increase the jet noise by approximately 13 dB. The data show that this is roughly the case above 10 kHz. Thus,

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examining the farfield spectra above 10 kHz reveals noise generated by the trailing edge blowing slot.

Comparison with Equivalent Blowing Ratio

When comparing spectra for steady and pulsed blowing that represent a condition similar to Case 1 in Figure 2.5, it is expected that the averaged slot exit velocity should be equivalent to the steady jet velocity. Hence, the jet noise radiating to the farfield should be similar. Figure 5.2 shows a slot plenum pressure time history for a steady and pulse blowing case representing this case. Figure 5.3 shows the resulting farfield acoustic spectra at 30, 60, and 90 degrees. It is clear that the noise generated from the pulsed blowing case [in the region identified as noise due to the blowing jet, > 10 kHz] is on the order of the steady case, as expected.

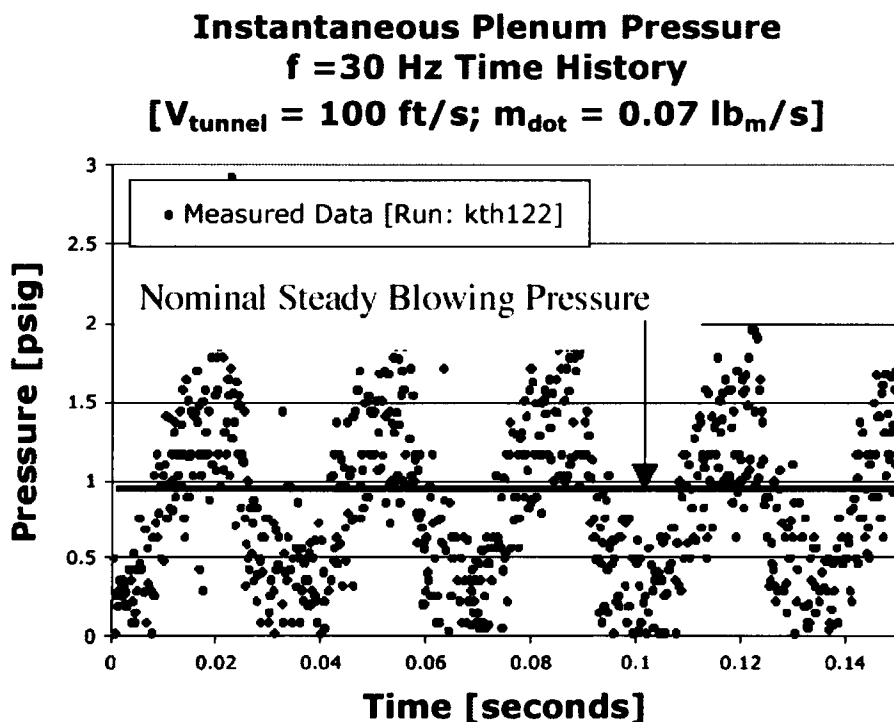


Figure 5.2 Slot plenum pressure time history for “equivalent lift” case.

It is also clear that noise levels below 1 kHz for the pulse blowing case are 5 – 10 dB higher than the steady blowing case. This suggests that part of the pulsing mechanism could be contributing to the noise in this region. Care was taken to place acoustic foam around the torque-motor, but the impulsive opening of the valve might be contributing to a wide-band noise below 1 kHz. In

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assessing whether a pulsing system would be viable for full scale use on an aircraft, the pulsing mechanism would have to be carefully designed to minimize its farfield radiated noise contribution. For the present study, focusing on the noise generated above 10 kHz is relevant for assessing the noise generated by a pulsed slot-jet at the wing trailing edge.

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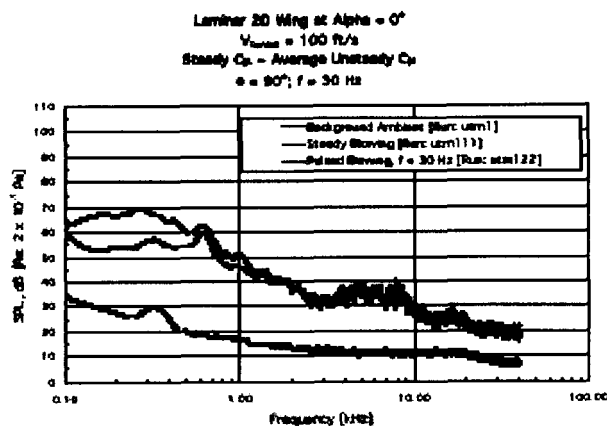
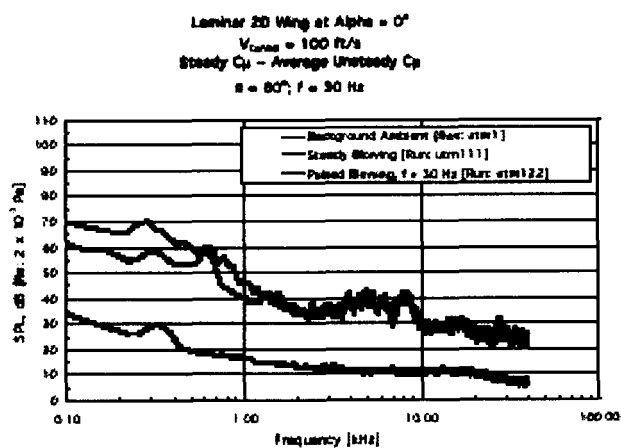
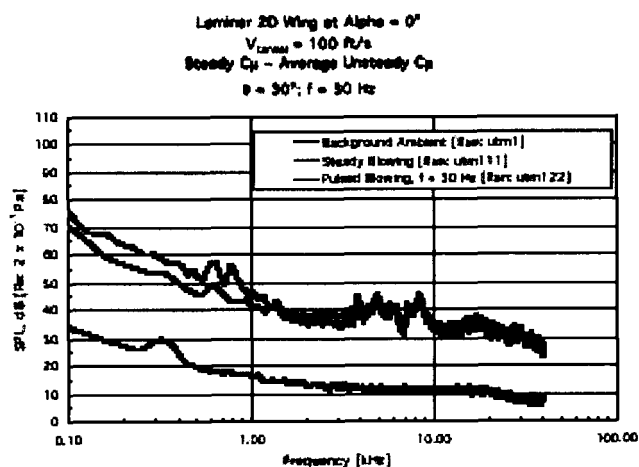


Figure 5.3 Comparison of farfield acoustic spectra for steady vs. pulsed blowing [$V=100$ ft/s, $f=30$ Hz]

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Comparison with Equivalent Lift

Using Figure 2.6 as a guide, one can see that for a case of equivalent lift, less mass flow is needed for the pulsing condition. Choosing a set of data at which the pulsed blowing mass flow is roughly 70% of the steady mass flow, a comparison can be made of the farfield jet noise. Figure 5.4 shows the farfield noise spectra of just such a case. Here it is observed that indeed a modest acoustic benefit is obtained with the pulsed blowing case at higher frequencies. At 30 degrees, it is as much as 5 –6 dB above 20 kHz. This reduction in jet noise is due to the fact that the average slot jet exit velocity is lower than the steady jet. This is a result of the unique aerodynamic benefit of pulse blowing, that is, not as much mass flow is required when pulsing.

6.0 Conclusions

In an effort to enhance the viability of the Circulation Control wing, pulsed rather than steady blowing has been investigated as a means of reducing the total amount of air needed for such a system. Indeed there is an aerodynamic benefit that can be realized with pulsing trailing edge flow. Within a certain range of blowing ratios, an increased amount of lift can be obtained for a given mass flow (See Figure 2.6). *The experimental results presented in this report suggest that there is potential to reduce the noise associated with a pulsed jet that issues from the trailing edge, if the noise in question is associated with the issuing jet only.* It is evident from the data that a quieter delivery system needs to be pursued if any serious attempt is made to integrate this concept on a large system.

A further important result from this program is the general lack of a robust, aeroacoustically designed, pulsing mechanism that could be used for this type of application. The field of active flow control in general, where pulsing flow is a very popular concept, is in need of devices that can pulse flow with good frequency response, amplitude, and quiet operation.

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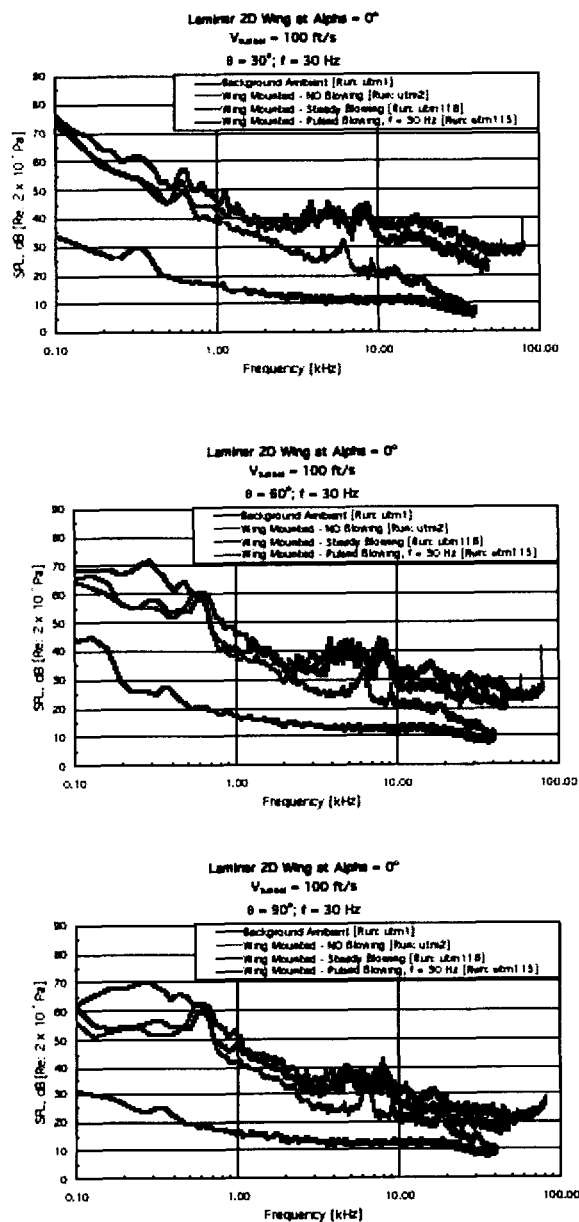


Figure 5.4 Comparison of farfield acoustic spectra for steady vs. pulsed blowing; “Equivalent Lift” [$V=100$ ft/s, $f = 30$ Hz]

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